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METHOD AND APPARATUS
FOR CONTROLLING
A SYNCHRONOUS RECTIFIER

5 This application claims the benefit of the provisional application Serial No. 60/368,508 filed on 29 March 2002 and entitled Driving Synchronous Rectifiers, which is incorporated by reference in its entirety.

BACKGROUND

10 The present invention is directed generally to the field of power electronics, and specifically to a method and apparatus for controlling a synchronous rectifier.

BACKGROUND

15 In order for any electric circuit or device (a "load") that runs on electricity to operate properly, electric power must be supplied to it; and this power must be supplied at levels of current and voltage, and within tolerances, that are specified for a particular load. A switched-mode power converter is a device that receives electric energy from a raw input source generally not suited for a load and supplies a regulated output of electric energy in a form and an amount that is suitable for a particular load.

20 A switched-mode power converter includes at least one primary switch that is used to switch a direct current input on and off to produce a time-varying voltage and current. The direct current input may be supplied by a battery or be derived by rectifying an alternating current. A switched-mode converter includes a magnetic storage element, which may be an inductor, and frequently is a transformer for
25 electrically isolating input from output. The time-varying voltage and current is coupled to the magnetic storage element. When the DC input is switched on, a magnetic field is induced in the magnetic storage element, and when the DC input is switched off, the magnetic field collapses, transferring the stored energy into an electrical current.

A switched-mode power converter also includes a circuit for controlling the primary switch or switches used to switch the input current on and off. The time period when the switch is closed is referred to as T_{ON} or simply the "on" period and the time period when the switch is off is referred to as T_{OFF} or simply the "off" period. A
5 switching time period T_S or "duty cycle" is defined as $T_S = T_{ON} + T_{OFF}$. The control circuit can regulate the amount of power that is delivered to the load by making the on period longer or shorter for a fixed duty cycle. Alternatively, the amount of power delivered can be regulated by making the duty cycle longer or shorter for a fixed on period. Because the output voltage of a switched-mode converter generally depends on
10 the input voltage, the duty cycle, and the load current, a feedback signal indicative of the output voltage or current is provided to the control circuit for use in regulating the duty cycle.

In addition to the primary switch, a switched-mode power converter commonly includes one or more switches that control the flow of current and prevent it from
15 flowing in certain directions within the converter circuit. These devices for controlling the flow of current in a switched-mode power converter are referred to herein as "secondary switches."

Switch mode power converters in a variety of topologies are known. Some of the primary topologies that use an inductor as the magnetic storage element are the
20 buck, boost, and buck-boost topologies. The buck topology is shown in Figure 1, the boost topology is shown in Figure 2, and the buck-boost topology is shown in Figure 3. Other important topologies that use an inductor as the magnetic storage element are the full-bridge, half-bridge, and Cuk topology. In Figures 1-3, the reference numbers 20 and 22 identify, respectively, the primary and secondary switches. In other topologies,
25 the primary and secondary switches are located similarly to the locations shown in Figures 1-3. In general, some of the principal switch mode power converter topologies that incorporate a transformer as a magnetic storage element to achieve electrical isolation include the flyback converter which is derived from the buck-boost converter, the forward converter which is derived from the buck converter, the forward-flyback
30 converter, the push-pull converter which is derived from the buck converter, and the

half-bridge and full-bridge converters which are derived from the buck converter. The forward converter, a modified version of the forward converter known as the two-transistor forward converter, the forward-flyback converter, and the half-bridge and the full-bridge converters have, in addition to a transformer, one or more inductors on the output or secondary side of the transformer that serve as additional magnetic storage elements.

In some topologies, energy is transferred to the magnetic storage element (or elements) and to the load during the T_{ON} portion of the duty cycle. This may be referred to as a forward transfer. The transfer of energy from the magnetic storage element to the load that occurs during the T_{OFF} portion of the duty cycle may be referred to as the flyback transfer. If the topology has two secondary switches and both switches conduct current during the flyback transfer, the topology is referred to as a symmetrical topology. On the other hand, if the topology has two secondary switches and one switch conducts only during the forward transfer and other conducts only during the flyback transfer, the topology is referred to as an asymmetrical topology. In addition, if the topology has only one secondary switch and the switch conducts during the forward and flyback transfer, the topology is considered an asymmetrical topology. Symmetrical topologies include the full-bridge, half-bridge, and push-pull. Asymmetrical topologies include the forward converter, the two-transistor forward converter, and the forward flyback converter with an active clamp. In addition, to the symmetrical and asymmetrical topologies, there is a third type of topology in which there is only one secondary switch and it conducts only during the flyback transfer. The flyback converter is an example of this third type of topology.

Diodes have traditionally been used as a secondary switch within switched-mode power converters. A diode has input and output terminals and may be either forward- or reverse-biased. An "ideal" diode will conduct a current when the input terminal is at a higher voltage than the output by a "cut-in voltage," that is, when it is forward-biased, and will not conduct when the voltage difference is below the cut-in voltage, that is, when it is reverse-biased. Thus, the diode acts as closed switch when it is forward-biased and as an open switch when it is reverse-biased.

An advantage of using a diode switch in a switched-mode power converter is its simplicity. However, diodes have a fixed forward voltage drop that is independent of the amount of current flowing in the diode. Typically, the voltage drop across a diode is on the order of 0.5 to 1 volt, or more. The electric power consumed by any device is the product of the voltage drop across it times the current through it. Because of the fixed forward voltage drop, high levels of power can be dissipated in the form of heat in a switched-mode power converter that uses ordinary diodes. Moreover, power losses increase significantly with the amount of current that flows in the diode. A special type of diode known as a Schottky diode has a smaller forward voltage drop than an ordinary diode, typically on the order of 0.15 to 0.45 volts. To achieve greater efficiency, Schottky diodes are commonly used as switches in switched-mode power converters.

Beginning with the invention of the transistor and later the integrated circuit, there has been and continues to be a trend to circuits with smaller and smaller features. In addition, there has been and continues to be a trend to circuits with higher and higher switching speeds. These trends are widely recognized. Within the field of power engineering, several related trends are recognized which concern the requirements of switched-mode power converters that supply power to these smaller and faster circuits. Specifically, switched-mode power converters must be made to fit within dimensions that are increasingly smaller, they must be able to supply voltages that are increasingly lower, and supply currents that are increasingly higher. For example, the typical required supply voltage has dropped from 5 volts to 3.3 volts, with devices in the near future expected to require only 1.5 volts. In addition, gigahertz switching speeds are now common and the current required in a circuit generally increases with frequency. Moreover, because many circuits today are battery powered so that devices incorporating them can be used with mobility, there is a need for switched-mode power converters that are ever more efficient. Yet another requirement of present electronic circuits stems from the power-saving "sleep mode" that many such circuits enter during periods of inactivity. A switched-mode power converter must be able to supply levels of energy for both normal and sleep modes. While Schottky diodes are more efficient

as secondary switches than ordinary diodes, further improvements in efficiency and miniaturization would be desirable.

A synchronous rectifier is a type of switch that is significantly more efficient than a diode. In addition, a synchronous rectifier permits the use of smaller magnetic and electric storage elements. A synchronous rectifier is typically a MOSFET (metal-oxide-semiconductor field-effect transistor) and bypass diode embedded within the same silicon structure. In comparison to the 0.15 to 0.45 voltage drop of a Schottky diode, the voltage drop across a MOSFET during conduction is typically less than 0.1 volt. A MOSFET is a three terminal device in which a current will flow between a source terminal and a drain terminal if a control signal is applied to a gate terminal, provided of course that the source and drain are at different voltages. (The MOSFET is operated in cut-off and saturation modes, and accordingly when the control signal is applied it must be sufficient to place the MOSFET in saturation.) The MOSFET stops conducting and acts like an open circuit when the control signal is removed from the gate. Thus, the MOSFET acts as closed switch when there is no control signal on the gate and as an open switch when a control signal is applied.

MOSFET devices have properties that can create problems in certain switched-mode power converters or under certain conditions. Unlike a diode, a MOSFET is capable of conducting current in either direction, that is, from drain to source or from source to drain. If the load transitions from a state where it needs a lot of power to one where it needs much less power, it is possible that current can flow within the converter circuit in reverse of the intended direction. Reverse current flow can mean that energy is transferred from the load to the input source, reducing converter efficiency. Thus, synchronous rectifiers have generally only been used if the direction of current flow can be guaranteed. Another potential problem arises from the fact that the primary switch in a switched-mode converter is commonly a power MOSFET. If the primary switch is turned on before the secondary switch has turned off, both MOSFETs will simultaneously conduct current, resulting in an undesirable "shoot-through" current.

A shoot-through current generates large power losses and leads to rapid failure of the switching devices. For this reason, the control synchronous rectifiers must also be precisely regulated.

As mentioned, the use of a diode as a secondary switch in a switched-mode power converter has the advantage of simplicity: a diode does not require a control signal. When a synchronous rectifier replaces a diode, some method for providing a control signal is required. One method for providing a control signal is the "self-driven" method. In the self-driven method, the gate of the synchronous rectifier is directly coupled to a secondary winding of a transformer. However, in some circuit topologies, it may not be possible to implement the self-driven method. In addition, the self-driven method may not provide the required degree of precision. Self-driven topologies are typically not suited for applications where the input power or required load power fluctuates. Further, self-driven topologies are typically not suited for situations where two or more converters are coupled in parallel to supply a single load. In another method, the output voltage may be used as a feedback signal for a secondary switch control circuit. The use of output voltage suffers from the problem that it typically changes too slowly to provide rapid feedback concerning changes in the power requirements of the load. This slow response to fast current transients fails to protect switches and leads to devices failure. In yet another method, the output current may be used as a feedback signal for a secondary switch control circuit. While output current changes faster than output voltage, providing faster feedback than the voltage method, the use of the output current requires a current sensor. Thus, a disadvantage of use output current as a feedback signal is that an additional component is needed, a component which reduces efficiency by adding output impedance.

Accordingly, there is a need for a method and apparatus for providing a control signal for controlling a synchronous rectifier that does not suffer from the disadvantages of the known methods for providing a control signal.

SUMMARY

The present invention is directed to a switch mode power converter for supplying an output power to a load. The switch mode power converter includes, in a preferred embodiment, a switching device having a switching input, a switching output, and a control input for enabling or disabling the switching device from conducting current from the switching input to the switching output. The converter preferably also includes a network in which the switching device input, the switching device output, and the load are connected together to form a circuit. The converter preferably also includes a bias winding in the circuit for producing a bias voltage representative of the output power, and a control circuit. The control circuit is for (a) determining the rate of change of the bias voltage, (b) characterizing the rate of change, and (c) controlling the control input as a result of the characterization (b).

DRAWINGS

- Figure 1 illustrates a known switch mode power converter in a buck topology.
- Figure 2 illustrates a known switch mode power converter in a boost topology.
- Figure 3 illustrates a known switch mode power converter in a buck-boost topology.
- Figures 4a-c illustrate a known switch mode power converter in a flyback topology.
- Figures 5a-f illustrate waveforms of voltages and currents in the converter of Figure 4 at different points in time.
- Figures 6a-b illustrate a switch mode power converter in a flyback topology according to one embodiment of the present invention.
- Figures 7a-g illustrate waveforms of voltages and currents in the converter of Figure 6a-b at different points in time.
- Figure 8 illustrates one embodiment of a control circuit of the present invention.
- Figure 9a illustrates a known switch mode power converter in a half-bridge topology.

Figure 9b illustrates a switch mode power converter in a half-bridge topology according to one alternative embodiment of the present invention.

Figure 10a illustrates a switch mode power converter in a two-transistor forward topology according to an alternative embodiment of the present invention.

5 Figure 10b illustrates a timing diagram of the waveforms of voltages and currents of the converter of Figure 10a at different points in time.

Figure 10c illustrates the logic diagram of the converter of Figure 10a.

10 Figure 11a illustrates a switch mode power converter in a forward-flyback topology with a current-doubler, synchronize rectification, and active clamp topology according to an alternative embodiment of the present invention.

Figure 11b illustrates a timing diagram of the waveforms of voltages and currents in the converter of Figure 11a at different points in time

Figure 12a illustrates a switch mode power converter in half-bridge topology according to an alternative embodiment of the present invention.

15 Figure 12b illustrates a timing diagram of the waveforms of voltages and currents in the converter of Figure 12a at different points in time.

Figure 12c illustrates a logic diagram of the converter of Figure 12a.

Figure 12d illustrates a timing diagram of the logic diagram of Figure 12c at different points in time.

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DESCRIPTION

The present invention is directed to a switch mode power converter for supplying an output power to a load. The switch mode power converter employs one or more synchronous rectifiers as secondary switching devices. In one preferred
25 embodiment, the synchronous rectifiers may be placed in parallel with discrete diodes. During light load operation, the synchronous rectifiers are disabled and current is conducted in the body diodes of the synchronous rectifiers or in the parallel discrete diodes. In one preferred embodiment, the power converter also includes a bias winding

for producing a bias voltage representative of the output power, and a control circuit. Light load conditions may be detected using the bias voltage. The control circuit is for (a) determining the rate of change of the bias voltage, (b) characterizing the rate of change, and (c) controlling the control input as a result of the characterization (b).

5 The present invention provides the benefits of using synchronous rectifiers as secondary switches during normal load conditions. In addition, the present invention allows for the use of either parallel diodes or body diodes during light load conditions. The present invention protects against reverse current flow during light load conditions because the reverse current must be driven by a voltage that exceeds the diode cut-in
10 voltage. Thus, in situations where two or more switch mode converters are connected in parallel to supply a single load and the output of one converter is at a slightly lower output voltage than the others, current will not flow into the lower voltage converter in reverse because the voltage difference would normally not be sufficient to overcome the diode cut-in voltage.

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Flyback Converter

Figures 4a-c and 5a-f respectively illustrate an idealized switched-mode flyback DC-DC converter and idealized waveforms depicting voltages and currents within the circuit at different points in time. As shown in Figure 4a, the flyback converter is
20 coupled to an input DC power source, which supplies an input voltage V_{in} , and to an output load represented by a resistor R_L . The flyback converter includes a switch SW on a primary side, and a diode D and a capacitor C on a secondary side of the circuit.

The flyback converter includes a transformer T which magnetically couples the primary and secondary sides of the circuit. The transformer T has primary and
25 secondary windings, L_1 and L_2 , and a transformer core TC. When a current passes through one winding, a voltage is induced in the other winding. The polarity of the induced voltage depends on how the two windings are wound and a dot convention is conventionally employed to indicate the polarity of the induced voltage. According to the dot convention, if a current enters the dotted terminal of one winding, a positive
30 voltage will be induced at the dotted terminal of the other winding.

The switch SW in the flyback converter may be open or closed. The time period when the switch SW is closed is referred to as T_{ON} or simply the "on" period and the time period when the switch is off is referred to as T_{OFF} or simply the "off" period. A switching time period T_S or "duty cycle" is defined as $T_S = T_{ON} + T_{OFF}$. During the on period, energy is stored in the transformer T. During the off period, the stored energy is transferred to the secondary side of the circuit. A current I_o flows in the load R_L during both the on and off periods. During the on period, energy that is stored in the capacitor C supports the current I_o .

Figure 4b illustrates how the flyback converter circuit effectively looks during an on period. A short circuit has been substituted in the figure for the switch SW because the switch is closed during the on period. When the switch SW is closed, a current I_{pri} enters the dotted terminal of the primary winding L_1 . The current I_{pri} induces a voltage in the secondary winding which, according to the dot convention, is positive at its dotted terminal and as a result, the diode D is reverse-biased. The diode D has been replaced with an open circuit in Figure 4b because it is reverse-biased. During the on period, the current I_{pri} flows in the primary winding L_1 , storing energy in the transformer T. Referring to Figures 5a, 5b, and 5c, it can be seen that during the on periods, the voltage V_{sw} across the switch is zero, the voltage V_{pri} across the primary winding is equal to the input voltage V_{in} , and the current I_{pri} in the primary winding ramps up with time. Since the diode D is reverse-biased during the on period, the current I_{sec} in the secondary winding L_2 is zero, as shown in Figure 5f.

Figure 4c illustrates how the flyback converter circuit effectively looks during an off period. An open circuit has been substituted in the figure for the switch SW because the switch is open during the off period. After the switch is opened, the polarity of the voltage V_{pri} across the primary winding L_1 reverses which in turn causes the voltage V_{sec} across the secondary winding L_2 to reverse its polarity. The reversal of polarity in the secondary winding L_2 causes a current I_{sec} to flow in the secondary winding. In addition, the diode D is forward-biased during the off period as a result of the reversal of polarity in the secondary winding L_2 . For this reason, the diode D has been replaced with a short circuit in Figure 4c. Referring to Figures 5a, 5b, and 5c, it

can be seen that during the off periods, the voltage V_{sw} across the switch is positive, the voltage V_{pri} across the primary winding is negative, and the current I_{pri} in the primary winding L_1 is zero. Because the diode D is forward-biased during the off period, the current I_{sec} in the secondary winding L_2 ramps down with time, as shown in Figure 5f.

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Synchronous Rectification - Flyback Topology

One preferred embodiment of the present invention is shown in Figures 6a-b. A flyback converter (the "SR flyback converter") which employs a synchronous rectifier is illustrated in Figures 6a-b and waveforms depicting voltages and currents in the circuit at different points in time are shown in Figures 7a-g. As shown in Figure 6a, the SR flyback converter is coupled to an input DC power source, which supplies an input voltage V_{in} , and to an output load represented by a resistor R_L . The SR flyback converter includes a switch SW on a primary side, and a synchronous rectifier SR , a Schottky diode D , and a capacitor C on a secondary side of the circuit. In addition, the SR flyback converter includes a control circuit CC for generating a control signal V_{C-SW} for the switch SW and a control signal V_{C-SR} for the synchronous rectifier SR .

As shown in Figures 6a-b, the SR flyback converter includes a transformer T which magnetically couples the primary and secondary sides of the circuit. The transformer T has primary and secondary windings, L_1 and L_2 , and a transformer core TC . The dots shown adjacent to one terminal of the primary and secondary windings, L_1 and L_2 , are placed according to the dot convention. The dots for the windings are placed in the same position as those for the flyback converter of Figures 4a-c. The SR flyback converter additionally includes a bias winding, L_B . The bias winding L_B is coupled to the control circuit CC so that it can provide it with a bias voltage V_B and a bias current.

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As with the flyback converter of Figures 4a-c, the switch SW in the SR flyback converter may be open or closed. Similarly, the SR flyback converter has a "duty cycle" that is defined by $T_s = T_{ON} + T_{OFF}$. Moreover, the SR flyback converter operates similarly to the flyback converter shown in Figures 4a-c. During the on period of the

SR flyback converter, energy is stored in the transformer T and during the off period, the stored energy is transferred to the secondary side of the circuit.

Unlike the flyback converter of Figures 4a-c, the SR flyback converter includes the synchronous rectifier SR and has two modes of operation. In "normal" mode, the synchronous rectifier SR is enabled and in the "light load" mode, it is disabled. Under conditions when the load R_L is deemed to be normal, the synchronous rectifier SR performs a switching function similar to the diode D illustrated in Figures 4b-c. However, under conditions when the load R_L is deemed to be "light," the synchronous rectifier SR is disabled and the switching function is performed by the diode D. Figure 6b illustrates how the SR flyback converter circuit effectively looks under light load conditions. In Figure 6b, because the synchronous rectifier is disabled during the light load period, a short circuit has been substituted for the synchronous rectifier SR.

Referring to Figures 7a-b, and 7d-g, it can be seen that during the on periods, the voltage V_{sw} across the switch is zero, the control signal V_{C-SW} for the switch SW is high and the voltage V_{sec} across the secondary winding L_2 is negative. Because the voltage V_{sec} is negative, the diode D is reverse-biased. In addition, the control signal V_{C-SR} for the synchronous rectifier SR is low, indicating that it is turned off. Because the diode D is reverse-biased and the synchronous rectifier SR is off, the currents I_{DI} and I_{SR} in the diode D and the synchronous rectifier SR, respectively, are zero.

Figures 7b, 7d, and 7e show arrows that will be understood by one skilled in the art, but which may require explanation for others. The arrows illustrate cause and effect relationships. The solid circle at the tail of an arrow indicates a signal transition or level that causes some action and the point of the arrow indicates the action caused. For instance, the transition of V_{S-SW} (see Figure 7b) from a low to a high at the start of on periods 1 and 2 causes the signal V_{C-SR} to transition from a high to a low at the times indicated in Figure 7e.

The SR flyback converter operates in one of its two modes of operation during the off period. Referring to Figures 7a-b, it can be seen that the voltage V_{sw} across the switch is positive and the control signal V_{C-SW} for the switch SW is low during the off periods. The mode of operation for normal load conditions is shown for off periods 1

and 2, and the mode for light load conditions is shown for off period 3. Referring to Figure 7e, it can be seen that, during the normal load off periods 1 and 2, the control signal V_{C-SR} for the synchronous rectifier SR is high, indicating that the SR is functioning as a closed switch. Referring to Figure 7f, it can be seen that the current I_{SR} flowing in the synchronous rectifier ramps down with time during off periods 1 and 2. Referring now to Figure 7e, it can be seen that, during the light load off period 3, the control signal V_{C-SR} for the synchronous rectifier SR is low, indicating that it is functioning as an open switch. Referring to Figure 7g, it can be seen that current I_{DI} in the diode ramps down with time during the light load off period 3. As Figures 7f-g show, current flows in either the synchronous rectifier SR or the diode during the off time.

Figure 7d shows the voltage V_{sec} across the secondary winding L_2 . A reference threshold voltage V_{TH} is also shown. In contrast to the idealized waveform of Figure 5d which shows the voltage V_{sec} across the secondary winding L_2 becoming instantly positive at the end of the on period, the voltage V_{sec} that is shown in Figure 7d illustrates a more realistic view of the transition that occurs at the end of the on period. The voltage does not rise instantly; instead, it rises with a delay that defines an upward sloping line. (The voltage V_{sec} shown is somewhat exaggerated for purposes of clarity of illustration.) At the end of the on period, a V_{DELAY} signal goes high, as shown in Figure 7c. After a delay period, the V_{DELAY} signal goes low. During the delay period, the voltage V_{sec} is compared with the threshold voltage V_{TH} , as shown in Figure 7e. The control signal V_{C-SR} for the synchronous rectifier SR is enabled if the voltage V_{sec} becomes greater than the threshold voltage V_{TH} during the delay period, otherwise, the control signal V_{C-SR} is disabled.

Figure 8 shows one embodiment of a control circuit CC, which includes a comparator 100, an RS latch 102, a delay block 104, an inverter 106, and AND gates 108 and 110. The control signal V_{C-SW} is coupled to the inputs of the RS latch 102, the delay block 104, and the inverter 106. The voltage V_{sec} is coupled to the non-inverting input of the comparator 100 and the threshold voltage V_{TH} is coupled to inverting input

of the comparator 100. The output of AND gate 110 is the control signal V_{C-SR} for the synchronous rectifier SR.

In operation of the control circuit CC shown in Figure 8, the control signal V_{C-sw} is low during an off period. The control signal V_{C-sw} causes a low signal to be placed on the R input of RS latch 102. In addition, it causes a delay period to begin at the start of the off period. During the delay period, the delay block causes a high signal to be placed on one input of the AND gate 108. An inverted version of V_{C-sw} (a high signal) is placed on the other input of the AND gate 108 during the off period, as a result of the inversion performed by inverter 106. Thus, during the delay period, the output of the AND gate 108 is high, which enables the comparator 100.

When the delay period ends, the comparator 100 is disabled. At the start of the off period, the voltage V_{sec} across the secondary winding L_2 is negative, beginning its rise to a positive voltage. Thus, the output of the comparator 100 is low at the start of the off period and the output of the comparator 100 will go high when the voltage V_{sec} exceeds the threshold voltage V_{TH} . If it does go high during the delay period, the RS latch 102 will enter a set state, latching a high signal on its output and the input to the AND gate 110. Because the other input on the AND is high as a result of the inversion of signal V_{C-sw} , the output of AND gate 110 will also go high during the off period. Since this output is control signal V_{C-SR} for the synchronous rectifier SR, it is turned on during the off period.

If, on the other hand, the voltage V_{sec} does not exceed the threshold voltage V_{TH} during the delay period, the comparator 100 will be disabled while its output is low. As a result, the RS latch 102 will remain in a latched state, latching a low signal on its output and the input to the AND gate 110. Since, the AND gate's output control signal V_{C-SR} is low, the synchronous rectifier SR will be turned off during the off period.

Use of the Voltage in the Bias Winding

In the description of the operation of the SR flyback converter illustrated in Figures 6a-b, it was shown how the voltage V_{sec} across the secondary winding L_2 is compared with the threshold voltage V_{TH} during a delay period to determine whether

the control signal V_{C-SR} should be enabled or disabled. The use of voltage V_{sec} illustrates but one preferred voltage that may be compared with the threshold voltage V_{TH} , according to the present invention. In another preferred embodiment of the present invention, the bias voltage V_B , that is provided by the bias winding L_B shown in
5 Figures 6a-b, may be compared with the threshold voltage V_{TH} .

Transformers generally have leakage inductance, usually modeled as an additional inductance L_d in series with the secondary winding L_2 . Any inductive element, such as the leakage inductance L_d , will resist and hence delay any change in the current flowing through the element. As previously described, the polarities of the
10 voltages across the primary winding L_1 and the secondary winding L_2 reverse when the primary switch is opened. However, these polarity changes do not occur precisely simultaneously. The change in polarity occurs first in the primary winding L_1 , with the change in polarity in the secondary winding L_2 occurring at a slower rate than in the primary. The rate of change of the polarity in the secondary winding L_2 depends on the
15 leakage inductance L_d as well as the amplitude of the output current and other factors.

It is believed that the bias voltage V_B provided by the bias winding L_B reflects a polarity change with less delay from that in the primary winding L_1 than the voltage V_{sec} across the secondary winding L_2 . This property of the bias voltage V_B is believed to be due to the fact that the bias winding L_B carries a current that is low in amplitude in
20 comparison to the output current. The bias winding L_B is typically employed to provide electric power to the control circuitry of the power converter, circuitry which requires only a modest amount of current. For this reason, it is believed that the bias voltage V_B may be advantageously compared with the threshold voltage V_{TH} to provide an earlier indication of when the polarity across the primary winding L_1 has changed. As
25 mentioned, methods for controlling secondary synchronous rectifier switches that rely on sensing output current may not drive the synchronous rectifiers with adequate precision and they require a current sensor. Precision may be lacking because the output current can vary greatly during the delay period. In contrast, use of the bias voltage V_B provides an earlier indication of the polarity change in the primary
30 winding L_1 allowing the synchronous rectifiers to be driven more precisely. In

addition, the use the bias voltage V_B provides the advantage that is does not require an additional current sensor component, as it employs an existing component of the power converter, namely the bias winding L_B .

It should be understood that the present invention may be practiced with a bias winding L_B located on either the primary or secondary side of the transformer. In addition, the bias winding L_B may be additionally employed to supply power to a control or other circuit, or the bias winding L_B may be employed solely for the purpose of providing a bias voltage V_B for comparison with the threshold voltage V_{TH} . In addition, the bias winding L_B may be all or part of either the primary or secondary windings L_1 , L_2 of the transformer. Further, the bias winding L_B may be provided in a topology that does not include a transformer, such as those shown in Figures 1-3.

Control of Synchronous Rectifiers in Other Topologies

The method and apparatus of the present in invention for controlling a synchronous rectifier used as secondary switch has been described herein in the context of one preferred embodiment, namely the SR flyback converter. It should be understood, however, that the present invention was described in the context of the SR flyback converter for the purpose of clarity, that is, the features of the invention may be more readily understood in the context of a topology that does not include a large number of components and signals. But it should be understood that the present invention is not limited to the SR flyback converter. As will be appreciated by one skilled in the art, the present invention may be advantageously employed in any topology which uses synchronous rectifiers. Specifically, the present invention may be employed in topologies that include a transformer and in those that do not. Further, the present invention may be employed in those topologies that have been previously described or referred to herein as well as in other topologies known in the art. Figures 10a-b, 12a-b, and 13a-b, which are briefly described below, provide additional illustrations of topologies in which the present invention may be advantageously employed.

Figure 10a illustrates a switch-mode power converter that is based on a known two-transistor forward topology, according to one alternative preferred embodiment of the present invention. In known forward switch-mode power converters, the drive signals for the secondary switches such as $V_c(SR1)$ and $V_c(SR2)$ are determined by the drive signals for the primary switches and the output current. A disadvantage of the known half-bridge converter is that the synchronous rectifiers may be turned on before the voltage changes in the secondary winding. In addition, the current sensor is an extra component, a component that introduces an impedance in the output, an impedance which causes a reduction in efficiency.

Referring to Figure 10a, the parallel diodes shown on the secondary side and coupled to the circuit by dashed lines may be either body diodes of the synchronous rectifiers SR1 and SR2 or additional discrete diodes. The half-bridge converter includes a bias winding N_f from which a bias voltage V_f is derived. A control circuit, which is not shown in Figure 10a, generates two drive signals, $V_c(SR1)$ and $V_c(SR2)$, that are shown and used to control synchronous rectifiers SR1 and SR2. This control circuit functions in a similar manner to the control circuit previously described for the SR flyback converter, however, it is not identical to the previously described control circuit. The operation of this control circuit can be best understood by reference to Figure 10b.

As can be seen in Figures 10b, the bias voltage V_f is compared with threshold voltages V_{TH1} and V_{TH2} during a first and second delay periods δ . From the arrows having their tails on the transitions of either the primary control voltage $V_c(S1)$ or the bias voltage V_f and their heads pointing to transitions of $V_c(SR1)$ and $V_c(SR2)$, it can be seen that when the bias voltage V_f transitions past the threshold voltage during a delay period δ , the effect is a change in the level of the control signals for the synchronous rectifiers $V_c(SR1)$ and $V_c(SR2)$. The signal $V_c(SR2)$ is driven low when $V_c(S1)$ goes high and is driven high when V_f exceeds the threshold voltage during the delay period δ . The signal $V_c(SR1)$ is driven high when V_f becomes more negative than the threshold voltage during the delay period δ and is driven low when V_f becomes more positive than the threshold voltage during the delay period δ . The foregoing

transitions correspond to periods when the load, represented by R_O , is considered heavy. During periods when the load is considered light, it can be seen from an arrow L having its tail on the dotted line adjacent to the rising edge of a bias voltage V_f transition and its head on the transition of the disable signal to "disable on" that the control signals $V_c(SR1)$ and $V_c(SR2)$ are made inactive following this transition. In other words, when the delay in the rise in the bias voltage V_f is such that it does not exceed the threshold voltage V_{TH1} during the delay period δ , the synchronous rectifiers SR1 and SR2 are disabled and currents are conducted instead through the parallel diodes on the secondary side which are coupled to the circuit by dashed lines.

In Figure 10C is presented the logic diagram associated with the timing diagram of Figure 10B. In Figure 10C the $V_c(S1)$ 110 is applied to an Inverter 170 and after that to an AND gate 190. If the enable signal 750 is high then the $V_c(SR2)$ 104 is the inverted signal of $V_c(S1)$ though the rising edge will occur only during the time interval 108 after the falling edge of 110, when V_f 106 is higher than V_{th1} 114. If this condition does not occur during the time interval 108 the enable will have a low logic level and the output of 190 will be low as well. The gate 176 enables the comparator 180 during the time interval δ .

During the time interval δ after the rising edge of 110, and during the time interval δ 108 after the falling edge of 110, the comparator 182 is activated. If V_f 106 is lower than V_{th2} 116, then the Q output of 186 will be high and the output of gate 188 will be high as well. This controls the rising edge of $V_c(SR1)$ 102.

The falling edge of 102 will occur during the time interval δ after the falling edge of $V_c(S1)$. During that time 182 will be activated again. If V_f 106 is higher than V_{th2} 116 during the time interval δ then the output Q of 186 will go logic low and the output of 188 will go low as well. In the event wherein this condition does not occur during the time interval δ then 186 will be reset and the output Q of 186 will go logic low and the output of 188 will go low. The time interval δ can be different after the falling edge and rising edge of the primary control switch.

Figure 11a illustrates a switch mode power converter in a topology known as forward-flyback with current-doubler, synchronizous rectification, and active clamp

according to an alternative embodiment of the present invention. Figure 11a is a representative example of an asymmetrical topology. In asymmetrical topologies, one secondary switch conducts during the forward transfer of power and one secondary switch conducts during the flyback transfer. The method and apparatus of the present invention may be advantageously employed in controlling the secondary switch that conducts during the flyback transfer.

Referring to Figure 11a, the parallel diodes shown on the secondary side and coupled to the circuit by dashed lines may be either body diodes of the synchronous rectifiers SR1 and SR2 or additional discrete diodes. The two-transistor forward converter includes a bias winding N_f from which a bias voltage V_f is derived. A control circuit, which is not shown in Figure 10a, generates two drive signals, $V_c(\text{SR1})$ and $V_c(\text{SR2})$, that are shown and used to control synchronous rectifiers SR1 and SR2. This control circuit functions in a similar manner to the control circuit previously described for the SR flyback converter, however, it is not identical to the previously described control circuit. The operation of this control circuit can be best understood by reference to Figure 11b.

Figure 11b shows a timing diagram of the waveforms of voltages and currents in the circuit of Figure 11a at different points in time. As can be seen in Figures 11b, the bias voltage V_f is compared with threshold voltages V_{TH1} and V_{TH2} during a first and second delay periods δ . From the arrows having their tails on transitions of either the primary control voltage $V_c(\text{S1})$ or the bias voltage V_f and their heads pointing to transitions of $V_c(\text{SR1})$ and $V_c(\text{SR2})$, it can be seen that when the bias voltage V_f transitions past the threshold voltage during a delay period δ , the effect is a change in the level of the control signals for the synchronous rectifiers $V_c(\text{SR1})$ and $V_c(\text{SR2})$. The signal $V_c(\text{SR2})$ is driven low when $V_c(\text{S1})$ goes high and is driven high when V_f exceeds the threshold voltage during the delay period δ . The signal $V_c(\text{SR1})$ is driven high when V_f becomes more negative than the threshold voltage during the delay period δ and is driven low when V_f becomes more positive than the threshold voltage during the delay period δ . The foregoing transitions correspond to periods when the load, represented by R_O , is considered heavy. During periods when the load is considered

light, it can be seen from an arrow L having its tail on the rising edge of a bias voltage V_f transition and having two heads, one on the falling edge of $V_c(SR1)$ and the second head on the transition of the disable signal to "disable on" that the control signals $V_c(SR1)$ and $V_c(SR2)$ are made inactive following this transition. In other words,
 5 when the delay in the rise in the bias voltage V_f is such that it does not exceed the threshold voltage V_{TH2} during the delay period δ , the synchronous rectifiers SR1 and SR2 are disabled and currents are conducted instead through the parallel diodes on the secondary side which are coupled to the circuit by dashed lines.

Figure 12a illustrates a switch mode power converter in a half-bridge topology,
 10 according to yet another alternative embodiment of the present invention. Figure 12a is a representative example of a symmetrical topology. Figure 12b shows a timing diagram of the waveforms of voltages and currents in the circuit at different points in time.

It will be recalled that in symmetrical topologies both secondary switches
 15 conduct during the flyback transfer. In addition, both secondary switches transfer energy during the forward transfer. At the end of the forward cycle when one of the primary switches turns off, there is a voltage rise across the primary switches, a voltage rise which is a function of the loading conditions. As the load increases, the slope of the voltage rise across the primary switches also increases.

20 Referring to Figure 12a, the parallel diodes shown on the secondary side and coupled to the circuit by dashed lines may be either body diodes of the synchronous rectifiers SR1 and SR2 or additional discrete diodes. The half-bridge converter includes bias windings L_{B1} and L_{B2} from which bias voltages V_{f1} and V_{f2} are derived. A control circuit, which is not shown in Figure 10a, generates two drive signals, $V_c(SR1)$
 25 and $V_c(SR2)$, that are shown and used to control synchronous rectifiers SR1 and SR2. This control circuit functions in a similar manner to the control circuit previously described for the SR flyback converter, however, it is not identical to the previously described control circuit. The operation of this control circuit can be best understood by reference to Figure 12b.

As can be seen in Figures 12b, the bias voltages V_{f1} and V_{f2} are compared with threshold voltages V_{TH1} and V_{TH2} during a delay period δ . From the arrows having their tails on the transitions of either the primary control voltages $V_c(S1)$ or $V_c(S2)$, or the bias voltages V_{f1} and V_{f2} and their heads pointing to transitions of $V_c(SR1)$ and $V_c(SR2)$, it can be seen that when the bias voltages V_{f1} and V_{f2} transition past the threshold voltages during a delay period δ , the effect is a change in the level of the control signals for the synchronous rectifiers $V_c(SR1)$ and $V_c(SR2)$. The signal $V_c(SR2)$ is driven low when $V_c(S1)$ goes high and is driven high when V_{f2} exceeds the threshold voltage during the delay period δ . The signal $V_c(SR1)$ is driven low when $V_c(S2)$ goes high and is driven high when V_{f1} becomes more positive than the threshold voltage during the delay period δ . The foregoing transitions correspond to periods when the load, represented by R_O , is considered heavy. During periods when the load is considered light, it can be seen from an arrow L having its tail on the dotted line adjacent to the rising edge of a bias voltage V_{f2} transition and its head on the transition of the disable signal to "disable (SR2) and disable (SR1)" that the control signals $V_c(SR1)$ and $V_c(SR2)$ are made inactive following this transition. In other words, when the delay in the rise in the bias voltage V_{f1} is such that it does not exceed the threshold voltage V_{TH1} during the delay period δ , the synchronous rectifiers SR1 and SR2 are disabled and currents are conducted instead through the parallel diodes on the secondary side which are coupled to the circuit by dashed lines.

The present invention may be advantageously employed in controlling both of the secondary switches during the flyback transfer. It will be noted that the bias voltage may be sensed in either the high current secondary winding or in the lower current windings shown on the primary side. Figure 12b shows a timing diagram of the waveforms of voltages and currents in the circuit at different points in time.

In Figure 12C is presented the logic diagram which controls the Synchronized Rectifiers according with the time diagram of Figure 12B. The logic diagram of Figure 12C is for $V_c(SR2)$ but it is identical for the $V_c(SR1)$ with the difference that the input signal in A 514 will be $V_c(S2)$ and V_{f1} will replace the V_{f2} and the V_{th2} will be replaced by V_{th1} .

The key waveforms of logic diagram of Figure 12C is presented in Figure 12D. On line 500 is presented the input signal A 514, on line 502 is presented the signal after the delay cell 454. The output signal 518 of the gate 458 is connected to the reset input of 462. The output signal 520 of the gate 456 is enabling the comparator 464 during the time interval δ 416. If the output of 464 is high during 416 then Q output of 462 goes high and Vc(SR2) goes high as well. In the event wherein the output of 464 is not high during 416, then the output Q of 462 is maintained low and the Vc(SR2) skips the rising edge during this cycle.

Figure 9a shows a known switch-mode power converter in a half-bridge topology. The control signals Vc (SR1) and Vc (SR2) for the synchronous rectifiers SR1 and SR2 are determined by the control signals for the primary switches Vc (S1) and Vc (S2). The known power converter requires a current sensor shown on the line to the Load R_O. A comparator compares the sensed in current to a reference current and enables or disables the control signals based on this comparison.

Figure 9b shows a switch-mode power converter in a half-bridge topology according to the present invention. The control signals for the secondary rectifiers SR1 and SR2 are determined by the control signals for the primary switches Vc (S1) and Vc (S2), and by the rate of change of the voltage V_B in the bias winding. As previously described, under conditions when the load R_O is heavy or normal the rate of use of the voltage is such that the control signals for the synchronous rectifiers are enabled. Under conditions of light load R_O, the synchronous rectifiers are disabled.

The terms and expressions that have been employed in the foregoing specification are used as terms of description and not of limitation, and are not intended to exclude equivalents of the features shown and described or portions of them. The scope of the invention is defined and limited only by the claims that follow.